

A new star-forming region in Canis Major

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ABSTRACT

A new southern star-formation region, located at an estimated distance of ~ 1.5 kpc in the Lynds 1664 dark cloud in Canis Major, is described. Lynds 1664 contains several compact star clusters, small stellar groups, and young stars associated with reflection nebulae. Narrow-band $H\alpha$ and [SII] images obtained with 4-m CTIO telescope reveal more than 20 new Herbig-Haro objects associated with several protostellar outflows.

Key words: Herbig-Haro objects – ISM: jets and outflows – stars: pre-main-sequence.

1 INTRODUCTION

A group of the several faint nebulous objects were discovered around $RA = 7^h 24^m$ and $Dec = -24^d 30^m$ during a search for cometary nebulae and Herbig-Haro (HH) objects on the Palomar Observatory Sky Survey (POSS) images (Gyulbudaghian & Magakian 1977a,b,c). These nebulae are associated with the Lynds 1664 (L1664) dark cloud far from other well-known star forming complexes in Canis Major such as CMa OB1 and CMa R1. At the time of their discovery, the large negative declination prevented the acquisition of better data. Early surveys of this field identified several reflection nebulae that were listed in Brand, Blitz & Wouterloot (1986). However, in the subsequent decades, no additional data became available and these objects remained unstudied. In this paper, we present deep narrow-band $H\alpha$ and [SII] images of the L1664 cloud and report the discovery of several new HH objects tracing outflows from small clusters of young stellar objects (YSOs) detected on WISE satellite infrared images.

2 OBSERVATIONS

The images presented here were obtained on the nights of 13 May 2004 using the NOAO Mosaic II Camera CCD camera at the f/3.1 prime focus of the 4 meter Blanco telescope at the Cerro Tololo Interamerican Observatory (CTIO) near La Serena, Chile. Mosaic II camera is a 8192×8192 pixel array (consisting of eight 2048×4096 pixel CCD chips) with a pixel scale of $0.26'' \text{ pixel}^{-1}$ and a field of view $35.4'$ on a side.

Narrow-band filters centered on 6569\AA and 6730\AA with a FWHM bandwidth of 80\AA were used to obtain $H\alpha$ and [SII] images. A Sloan Digital Sky Survey (SDSS) i' filter

centered on 7732\AA with a FWHM of 1548\AA was used for continuum imaging. A set of five dithered 600 second exposures were obtained in $H\alpha$ and [SII] using the standard MOSDITHER pattern to eliminate cosmic rays and the gaps between the individual chips in Mosaic. A dithered set of five 180 second exposures were obtained in the broad-band SDSS i -band filter to discriminate between $H\alpha$, [SII], and continuum emission.

Images were reduced in the standard manner using IRAF. Following bias subtraction, cosmic ray removal, and flat fielding using dome flats, images were combined using the MSCRED package in IRAF.

3 RESULTS

3.1 HH objects and flows

Herbig-Haro objects are shocks powered by protostellar outflows. They can be identified as compact $H\alpha$ and $6716/6731\text{\AA}$ [SII] emission line sources without continuum emission in the SDSS i' band images. HH objects tend to have [SII] / $H\alpha$ surface-brightness ratios larger than ~ 0.5 while photo-ionized clumps have ratios smaller than 0.2. Thus, the intensity ratios of these emission lines, along with the presence or absence of i' band emission, can be used to discriminate between HH objects, photo-ionized gas, and reflection nebulae.

The area under investigation contains many small dark clouds in which several new groups of the HH objects were identified. However, outflow activity traced by HH objects is confined to a small portion of the L 1664 cloud. Figure 1 shows a wide-field $H\alpha$ image of the region. Most detected HH, listed in Table 1 in the order of their right ascension, are concentrated along a northeast-southwest line connecting three groups of small reflection nebulae around BBWo 22C, GM 1-8, and GM 3-7 nebulae. The new HH objects and their environments are described below.

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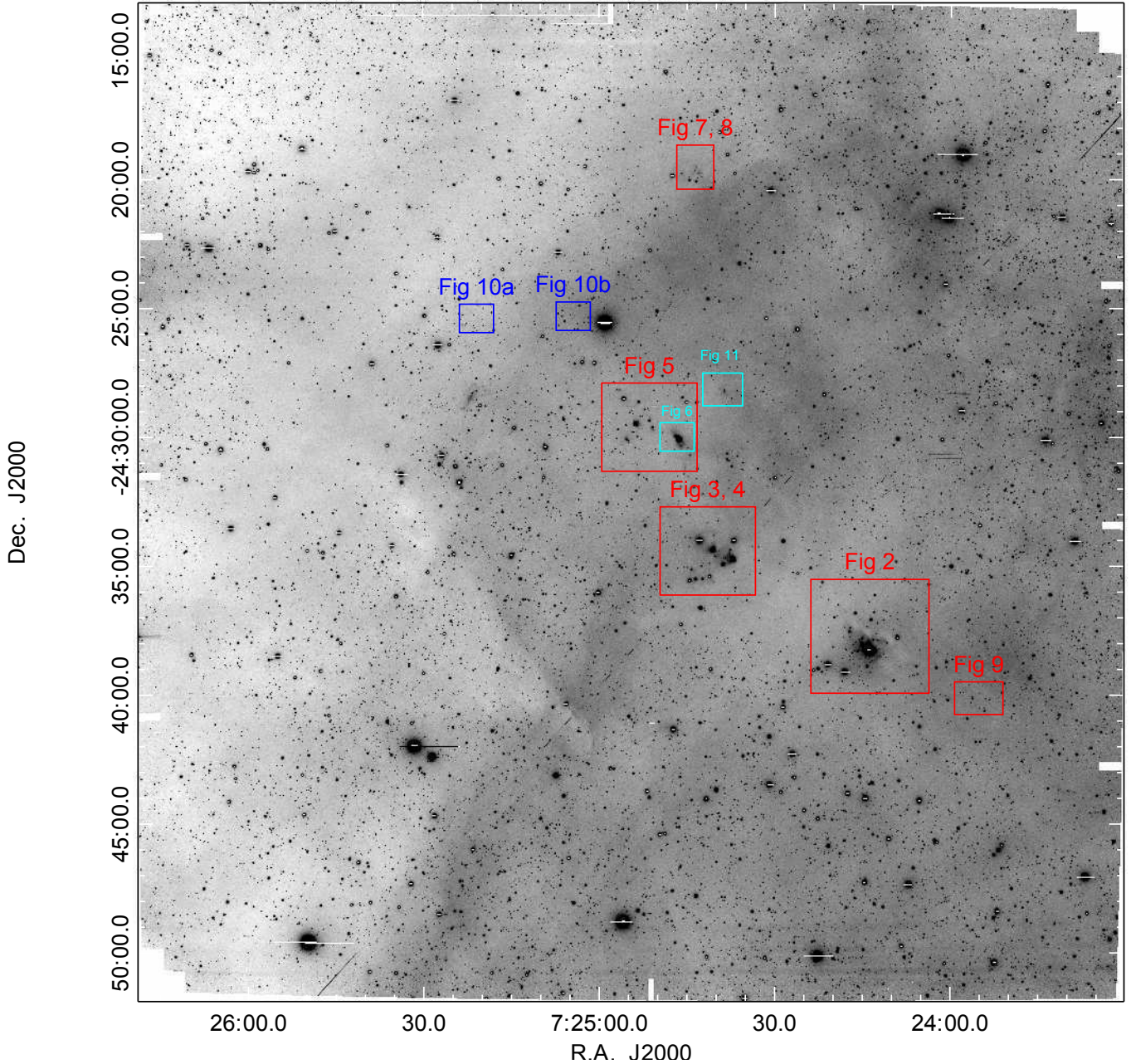


Figure 1. Whole observed field in $H\alpha$ filter. The areas, which are discussed in detail below, are shown by rectangles.

3.1.1 The BBWo 22C group

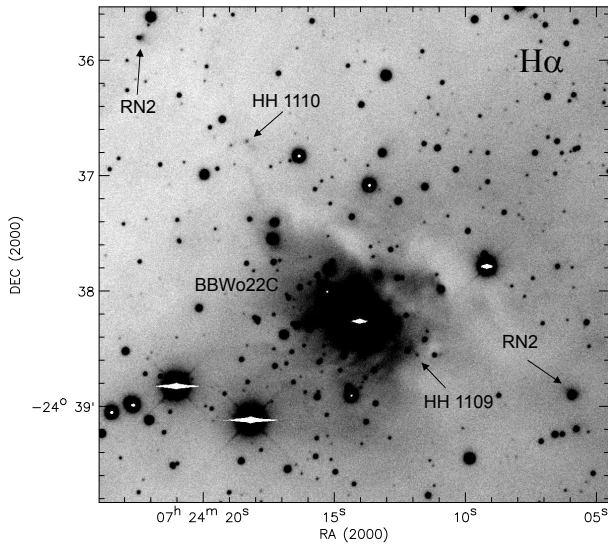
BBWo 22C (Figure 2) is a reflection nebula, located near the center of the L1664 dark cloud, that contains a small open cluster consisting of two dozen stars. The cluster was found by Ivanov et al. (2002) (numbered as CC 06) and by Dutra et al. (2003) (numbered as DBS 11) in the 2MASS survey. The cluster and reflection nebula are associated with the infrared source IRAS 07221-2531. The cluster is rimmed by several opaque cloudlets along its northern and western periphery. None of the stars seen at visual wavelengths appear to be particularly reddened and 2MASS does not reveal any objects seen only at infrared wavelengths. Two compact HH objects were found near this cluster (see Figure 2). HH 1109 is brighter in $H\alpha$ than [SII] and exhibits a short

tail extending towards the northeast which may indicate a bow-shock propagating towards the southwest. HH 1110 is an unresolved emission-line knot brighter in $H\alpha$ than [SII] located northeast of the cluster. The source(s) of these HH objects could either be cluster members or highly obscured young stellar objects embedded in the adjacent dark clouds. Proper motion measurements are needed to indicated the approximate locations of the driving sources.

This portion of L1664 contains two nebulous stars, RN 1 and RN 2, shown in Figure 2; their coordinates are listed in Table 2 with other reflection nebulae in this cloud. RN1 exhibits a fan of illumination toward the north; RN2 exhibits a fan of light extending from a dim star towards the west. Although both objects are visible in the WISE 3.6 and 4.5

Table 1. The coordinates of HH objects, HH flows and other emission objects in the field.

Name	RA(2000)	Decl.(2000)	Notes
HH 1108	7 23 55.1	−24 39 57	Streak with condensations
HH 1109	7 24 11.9	−24 38 33	To the SW from BBWo 22C
HH 1110	7 24 18.4	−24 36 42	To the NE from BBWo 22C
HH 1112	7 24 41.5	−24 34 15	To the NE from GM 2-20
HH 1111A	7 24 43.6	−24 19 32	} A separate flow from embedded source
HH 1111B	7 24 43.2	−24 19 46	
HH 1111C	7 24 43.0	−24 19 49	
HH 1111D	7 24 42.6	−24 19 45	
HH 1113	7 24 45.2	−24 33 40	To the NE from GM 2-20
HH 1114	7 24 45.4	−24 31 13	Star-like HH knot, connected with reflection nebula
HH 1120A	7 24 46.2	−24 33 05	Faint spot
HH 1120B	7 24 48.0	−24 33 00	} Two faint knots
HH 1120C	7 24 48.3	−24 32 59	
HH 1116	7 24 50.2	−24 29 23	Two faint knots
HH 1115	7 24 51.5	−24 29 23	HH jet from the star inside GM 2-21 nebula.
HH 1117	7 24 55.3	−24 28 39	Small knot
HH 1118A	7 24 56.6	−24 28 10	} Several bright knots in common nebula
HH 1118B	7 24 56.8	−24 28 11	
HH 1118C	7 24 57.0	−24 28 11	
HH 1119A	7 24 58.0	−24 31 12	} A dumbbell-like pair of HH knots
HH 1119B	7 24 58.7	−24 31 10	
Em.Obj. 1	7 25 04.4	−24 25 19	
Em.Obj. 2	7 25 20.9	−24 24 53	


Figure 2. An image of the area around BBWo 22C in H α . HH 1109, HH 1110 and other objects are marked.

μm images, neither is particularly prominent at these wavelengths. Comparison of the fluxes in the i' -band with the infrared images obtained by the Wide-field Infrared Survey Explorer (WISE) shows that RN2 is highly reddened but RN1 is not.

3.1.2 The GM 1-8 group

The GM 1-8 group (Figs. 3 and 4) contains two prominent northeast-facing cometary nebulae: GM 1-8 and GM 2-20 (BBWo 22E). Several nebulous streaks point radially away from the star located at the head of the GM 1-8 nebula.

The star at the apex of GM 1-8 was included in the Catalog of Galactic OB Stars (Reed 2003) as ALS 19644. It coincides with IRAS 07225-2428 (Garcia-Lario et al. 1997) (catalogued as GLMP 181) and is likely to be a moderate mass pre-main-sequence (PMS) object. Spectroscopy shows that H α along with the forbidden emission lines are in emission (Vieira et al. 2003; Sartori et al. 2010), confirming that it is a moderate-mass HAeBe star. It is very bright on the WISE images in all bands and its flux increases towards longer wavelengths. Thus this star must be surrounded by a dusty envelope. Another, fainter star is embedded in GM 1-8 approximately $4''$ to the northeast of the HAeBe star. However, no data constraining the nature of this object exists and it may be unrelated to star formation activity in L 1664 (it is not conspicuous at infrared wavelengths).

The nebula GM 2-20 also has a cometary morphology with the star in the tip of a red cone with same orientation as GM 1-8. The nebula contains a small nebulous arc emerging from the star. Compared to GM 1-8, its star is not bright in the WISE images especially at longer wavelengths. The SIMBAD coordinates for GM 2-20 and BBWo 22E are in error; these two designations refer to the same object. Soares et al. (2005) proposed that nearly all stars surrounding the GM 2-20 and GM 1-8 nebulae form a small cluster based on 2MASS images; the WISE images confirm this suggestion.

HH 1112 (Table 1), an oblong emission knot brighter in H α than [SII], is located near the northeast edge of the GM 2-20 reflection nebula. Another H α -dominated HH knot located further to northeast is designated HH 1113. HH 1120 is an extended object consisting of three diffuse knots (marked in Figure 3 as A, B and C) connected by a faint filament. Knots B and C are separated by only $4''$ to $5''$. HH 1112, HH 1113, HH 1120 and the central star in GM 2-

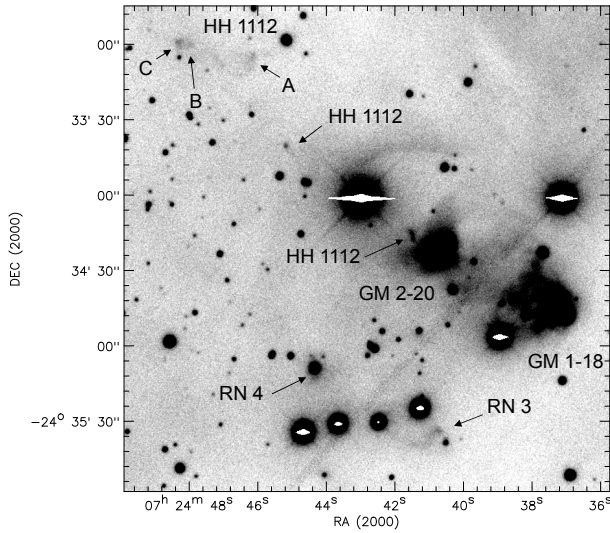


Figure 3. GM 1-8 and GM 2-20 area in $H\alpha$. HH 1112, 1113, 1120 and reflection nebulae are marked.

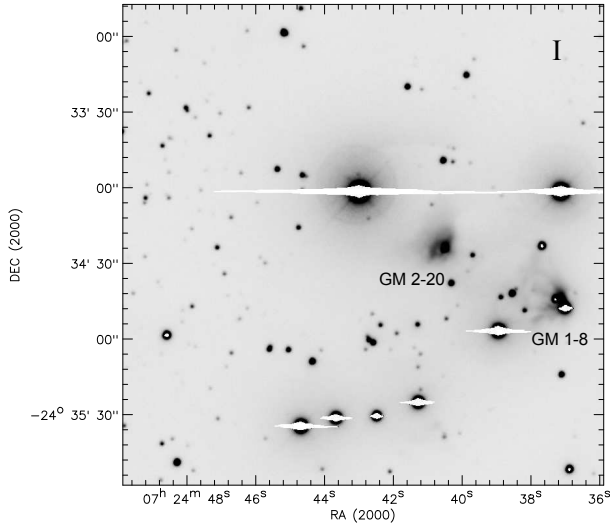


Figure 4. The same area as in Figure 3 in i' filter and with lower contrast, showing the inner structure of GM 1-8 and GM 2-20 nebulae, as well as the duplicity of the star in GM 1-8.

20 lie along a straight line. Thus, this star may be the source of an outflow driving these HH objects. HH 1120 resembles a fragmented bow shock at the end of a 2 arcminute-long outflow from the star embedded in GM 2-20.

Two additional reflection nebulae, RN 3 and RN 4 located approximately 1 arc-minute south of GM2-20, are marked in Figure 3. RN 3 is a faint, diffuse filamentary structure opening towards the northeast and possibly connected to a visually dim star that is bright in the K-band and WISE images. RN 4 is a star surrounded by dim nebulosity consisting of a mixture of emission and reflected light that is not conspicuous in IR images. A small knot to north-northeast of this star that is brighter in $H\alpha$ than [SII] may be another very faint HH object at $7^h 24^m 44^s.5 - 24^\circ 35' 04''$ (2000.0).

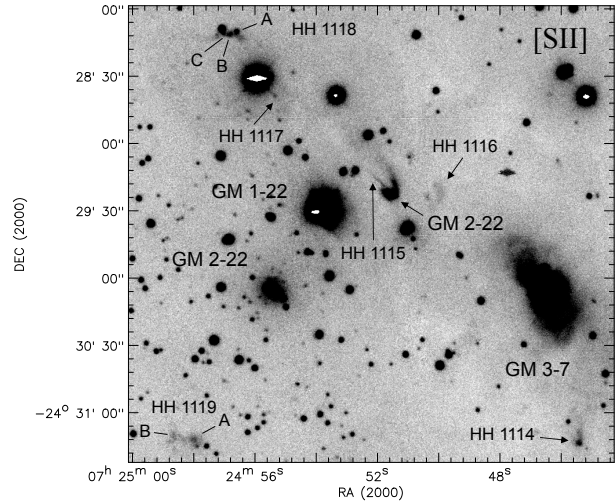


Figure 5. A [SII] image of the area surrounding GM 1-22 and GM 3-7. The HH objects, HH jets and reflection nebulae are labelled. Also note that GM 2-22 is a galaxy ZOAG G238.44-04.08.

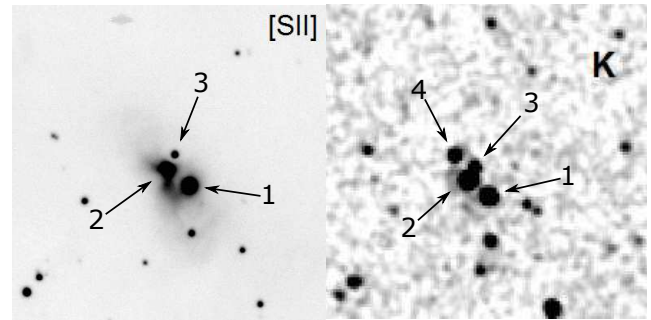


Figure 6. Enlarged images of GM 3-7, showing its inner structure in [SII] (left panel) and in K_s from 2MASS (right panel). Several embedded stars are labelled. The approximate size of each image is $105'' \times 105''$.

3.1.3 GM 3-7 group

GM 3-7 (BBWo 22F) is a compact nebula surrounding several stars (Figure 5) located further to the northeast (SIMBAD incorrectly listed it as identical to GM 2-21; see below). No HH objects were detected in this object whose inner structure is shown in Figure 6. At visual wavelengths, it includes two stars of nearly equal brightness (marked 1 and 2), as well as a fainter object (star 3). Star 2 is nebulous and bright in the K_s image; star 4 is also bright in the IR.

GM 1-22 (BBWo 22H) is a bright star on the edge of a dark cloud that illuminates compact fan-shaped reflection nebula with high surface brightness. There are no detected HH objects in this region.

During our early searches on POSS images, two small red nebulae were found near southeast and northwest sides of GM 1-22 (Gyulbudaghian & Magakian 1977b) and thought to be candidate HH objects and listed as GM 2-21 and GM 2-22. GM 2-22 (which is incorrectly labeled in SIMBAD as the same object as GM 1-22) is actually a galaxy which is listed as a zone of avoidance object ZOAG G238.44-04.08. GM 2-21 is a classical cone-shaped cometary nebula with a red star in the tip of the cone. It is associated with

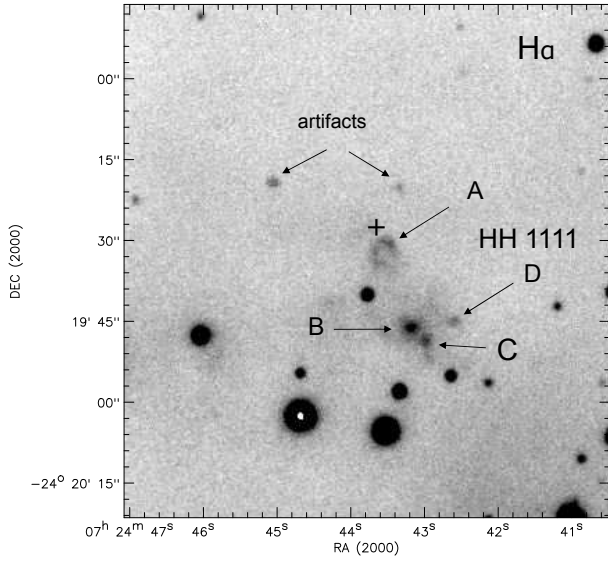


Figure 7. The HH flow near embedded IR source in H α emission. The individual knots are marked by letters. The position of IR star is shown by cross.

IRAS 07227-2423 located only in 11'' from this star. Its high brightness in the WISE images supports this identification.

Several HH objects were found in this field (Figure 5). HH 1114 is a nearly star-like emission knot dominated by [SII] emission but also visible in H α . It is accompanied by nebulous wisps of reflection nebulosity which are bright in the i' image. HH 1114 resembles a cometary nebula oriented roughly southwest-northeast with an emission-line core. The nebulosity is faintly detected in the J and H 2MASS images but in K $_s$ a star-like object coincides with the emission-line knot. This central star becomes more prominent at longer wavelengths in the WISE images. Thus HH 1114 is likely to be powered by a star heavily embedded in circumstellar dust. The existence of reflection nebula shows that some starlight escapes the dust envelope.

HH 1115, similar to HH 1114, is well-defined in [SII] and exhibits a collimated jet extending along the axis of the GM 2-21 nebula from the southwest to the northeast.

HH 1116 is a faint spot located west of GM 2-21 visible mainly in [SII]. HH 1117 is a compact knot brighter in H α . HH 1118 is similar in appearance in both [SII] and in H α and consists of three compact knots A, B and C (knot C is very close to a star) connected with a nebulous filament. HH 1117 and HH 1118 are located close to the axis of the HH 1115 jet and may trace additional shocks in the same outflow. HH 1119 consists of a pair of nebulous patches with a dumbbell shape brighter in [SII] than H α in a low extinction environment well separated from the other HH objects around GM 3-7.

3.1.4 A group near an embedded IR source

HH 1111, located near the edge of dark cloud far from the main area of HH activity in the L1664, is shown in Figure 7. The central star is invisible at visual wavelengths, seen in the 2MASS H-band, and especially bright in the K $_s$ image. In [SII] and H α several distinct emission knots are surrounded by extended nebulosity southwest of the infrared

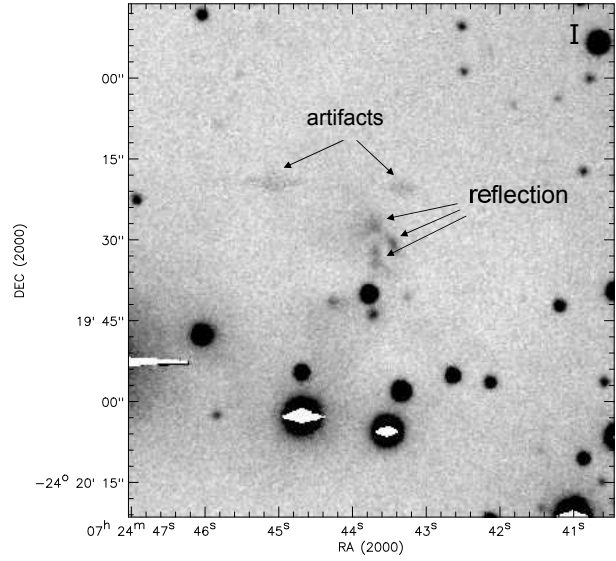


Figure 8. The same area in the i' filter. Instead of HH knots, one can see reflection patches, tracing the conical cavity.

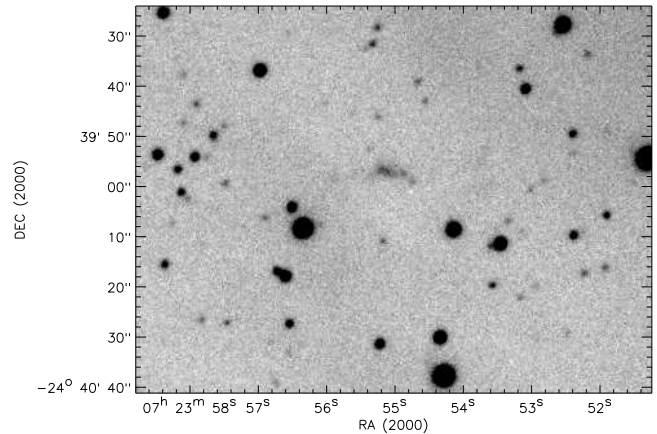


Figure 9. The H α image of HH 1108.

star. The knots, designated HH 1111 A, B, C, D in Figure 7, are totally absent in the i' image (Figure 8), but a few faint patches of reflection nebulosity tracing the walls of a conical cavity created by the outflow can be seen near the position of the knot A. The knots are distributed over a wide range of angles ($\sim 45^\circ$) with respect to the suspected source star. Thus, HH 1111 seems to trace a poorly-collimated flow.

3.1.5 HH 1108

This object resembles a streak with several condensations projected onto a dark cloudlet. It is brighter in H α than [SII] but has similar structure in both filters. Nothing is detected in i' or the 2MASS images. HH 1108, shown in Figure 9, is located far from the areas described above.

3.1.6 Emission objects of unknown nature

Two more emission-line objects shown in Figure 10 and listed in the Table 1 were found that cannot be unambigu-

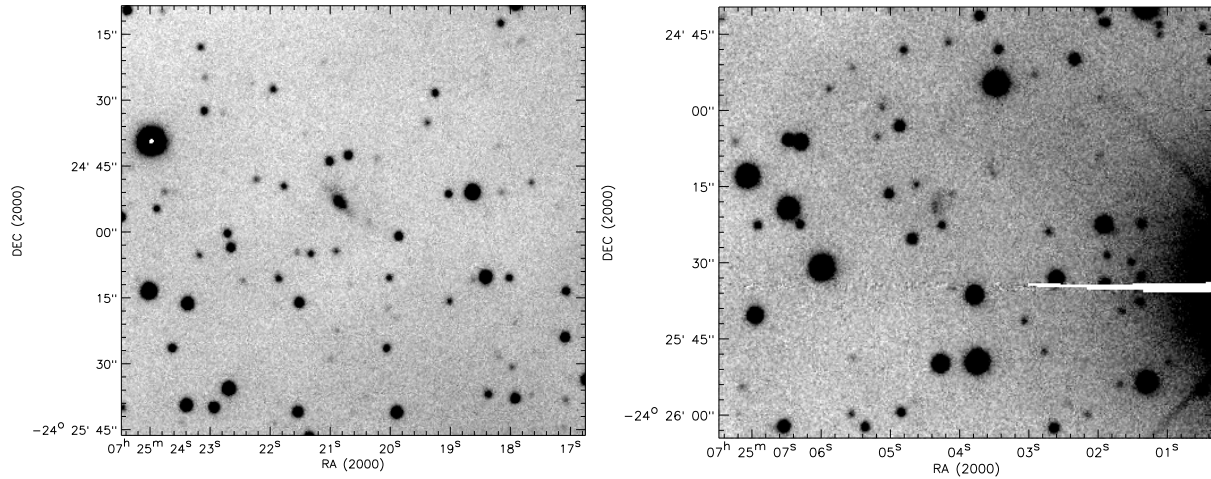


Figure 10. The $H\alpha$ images of Em. Obj. 1(right panel) and Em. Obj. 2 (left panel).

ously classified as HH objects. They might be planetary nebulae, distant HII regions, or genuine HH objects, but without spectra, classification is impossible.

Em. Obj. 1: This object is a tight group of emission knots brighter in [SII] than $H\alpha$. Nothing is found in 2MASS or WISE at its location. Although its remote location from the cloud makes it unlikely to be an HH object, it might be a remote, parsec-scale extension of the flow originating from GM 2-21 (see above). This object is located 300 arc-seconds from the apex of the cometary nebula GM 2-21 and within a few arc-seconds of the axis of the jet emerging from the embedded star.

Em. Obj. 2: This object's appearance is similar to an edge-on spiral galaxy, but it is invisible in i' and 2MASS. Its emission line character suggests that it might be a distant planetary nebula. One should note that the large diffuse object, seen in Fig.1 in 3 arc-minutes below the location of Figure 10a, and visible in both the narrow-band and the i' filters, is a background galaxy.

3.2 Reflection and cometary nebulae

The L1664 cloud contains many small reflection nebulae associated with one or more stars with strong infrared excess emission. Thus, this cloud is an example of an association of reflection nebulae (R-association in the older literature) tracing a loose group low- to intermediate mass young stellar objects. Some of these nebulae are associated with bright stars listed in BBWo and GM catalogues but never studied in detail. The new reflection nebulae reported here tend to trace objects whose illuminating stars are faint. Some are associated with HH objects or located near other outflows described above. All new and previously catalogued reflection nebulae are listed in Table 2 with updated coordinates. Short descriptions are given below.

RN 5: This nebula represents the edge of a dark cloudlet illuminated by one or two stars. RN 5 is located near the axis of the elongated ellipse which includes nearly all objects in this field. No emission lines were detected.

BBWo 22B: This bright, slightly nebulous star is located far from the field containing the HH objects.

RN 6: A compact and bright cometary reflection nebula

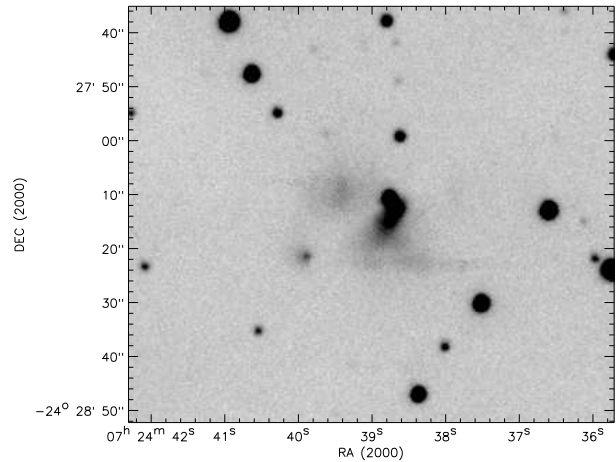


Figure 11. RN 6 reflection nebula in i' filter.

with traces of bipolar structure. Its central star is located near the edge of a region of high extinction (the same region includes GM 3-7) but it is not noticeably reddened (Figure 11).

RN 7 and RN 8: These are two nebulous stars, detected to the south of HH 1114.

BBWo 22G: This rather bright star with wisp of nebosity, similarly to BBWo 22B, is aside from the main area of HH-activity.

Figure 12 shows a thermal-infrared image obtained by the WISE satellite at 4.6 μm , 12 μm , and 22 μm . This image shows warm dust associated with BBWo 22C (Figure 2), a cluster of more than a dozen YSOs in the field containing GM 1-8 and GM 2-20 (Figures 3 and 4), about a dozen YSOs associated with GM 1-22, GM 2-21, and GM 3-7 (Figure 5), and a small group of YSOs in the field containing HH 1111 (Figures 7 and 8).

4 DISCUSSION AND CONCLUSIONS

The limited available observations do not allow a thorough analysis of this star-forming region whose distance remains

Table 2. The coordinates of the reflection and cometary nebulae in the field.

Name	RA(2000)	Decl.(2000)	Other names	Notes
RN 5a	7 23 40.1	−24 43 42		} Nebulous patch on the edge of dark cloudlet, with two stars
RN 5b	7 23 41.7	−24 43 40		
BBWo 22A	7 23 51.9	−24 46 00		
BBWo 22B	7 24 01.0	−24 24 04		Three stars of nearly equal brightness surrounded by nebula
RN 1	7 24 05.9	−24 38 53		Bright star with a very faint nebula
BBWo 22C	7 24 14.1	−24 38 16	GN 07.22.1, RK 71	Nebulous star near BBWo 22C
RN 2	7 24 22.5	−24 35 49		Includes IR cluster DBS 11 and IRAS 07221-2531
BBWo 22D	7 24 31.1	−24 41 37		Nebulous star near BBWo 22C
GM 1-8	7 24 37.0	−24 34 47	GLMP 181, PDS 250	Bright star with a very faint nebula
RN 6	7 24 38.8	−24 28 11		Associated with IRAS 07225-2428
GM 2-20	7 24 40.5	−24 34 23	BBWo 22E ^a	Typical cometary nebula on NW from GM 3-7
RN 3	7 24 40.8	−24 35 33		
RN 7	7 24 43.9	−24 31 57		Filamentary reflection nebula
RN 4	7 24 44.4	−24 35 08		A nebulous star
RN 8	7 24 46.2	−24 31 55		A nebulous star
GM 3-7	7 24 46.7	−24 30 00	BBWo 22F ^b	A star with nebulous fan
BBWo 22G	7 24 47.5	−24 41 20		Contains several stars
GM 2-21	7 24 51.4	−24 29 23		Bright star with a very faint nebula
GM 1-22	7 24 54.0	−24 29 30	BBWo 22H	Typical cometary nebula, a host for HH-jet HH 1115

^a in SIMBAD is identified incorrectly

^b in SIMBAD is incorrectly identified with GM 2-21

unknown. The small sizes of the reflection nebulae and HH objects, the high density of foreground stars despite the anti-center direction location of L1664 suggest that it is much farther than the Perseus, Orion, or the North America / Pelican Nebula complex in Cygnus. Several other dark clouds such as L1667, which contains the GM 1-46 nebula (Gyulbudaghian & Magakian 1977a) and the Bok globule L 1660, which contains HH 72 and several emission-line young stars and reflection nebulae (Reipurth & Graham 1988) are located within a half degree of the L1664 dark cloud. The [SII] and especially the H α images show extended diffuse emission on the Western side of L1664. This emission may belong to the large and diffuse HII region Sh-2 310. It is difficult to determine where the L1664 dark clouds are located – in foreground or behind the emission from Sh-2 310. However, the distances to these clouds and the HII region Sh-2 310 are controversial. Reipurth & Graham (1988) assumed that they were related to the Vela OB1 association at a distance of 1.5 kpc. Vieira et al. (2003) studied the central star (PDS 250) in GM 1-8 and its distance was found to be 2.46 kpc (kinematic distance from radio observations) or even 4.1 kpc (photometric distance).

L1664 dark cloud is associated with at least two photometrically studied IR star clusters. DBS 11, located inside the BBWo 22C reflection nebula and connected to two HH objects (see above), is definitely associated with L1664. Its (J–H), (H–K_s) diagram (Soares et al. 2008) demonstrates that the cluster contains low-mass young stars. Unfortunately, the distance was not estimated. The range of A_V from 9 to 17 magnitude, given by Ivanov et al. (2002) seems overestimated given their visibility in the images presented here.

Soares et al. (2005) studied the small cluster surrounding the GM 2-20 and GM 1-8 nebulae (see Figure 3). Using the J vs. (J–H) color-magnitude diagram, they estimate

the distance modulus J–M_J as 10.5 implying a distance of 1.3 kpc. Though this value is lower than estimated by Vieira et al. (2003), it seems in good agreement with the distance of Vela OB1. Finally, the distance to the well-studied cluster NGC 2362, believed to ionize the Sh-2 310 HII region, is established as 1.5 kpc (Dahm 2008).

Kumar et al. (2006) investigated the physical sizes of embedded young clusters, finding that half of the sample have effective radii of 1.5 pc. The half-light radii of the three small clusters in L1664 are about 100 arc-seconds. However, given the small numbers of stars, this is a highly uncertain number. If this corresponds to a length-scale of 1.5 pc, then the implied distance to L1664 is 2.1 kpc.

Thus, we assume that L 1664 and all objects inside it are located at D = 1.5 kpc. The full projected length of the long axis of the star forming region is about 8 pc. The longest confirmed flow in the field – from GM 2-21 to HH 1118 – has a projected length of 0.75 pc at this distance. If the HH object candidate Em.Obj.2 is confirmed to be an HH object and traces a distant shock in the outflow from GM 2-21, then this lobe of the outflow has a projected length of about 2.2 pc. If the cloud is at a distance of 2.1 kpc, all dimensions are larger by a factor of 1.4.

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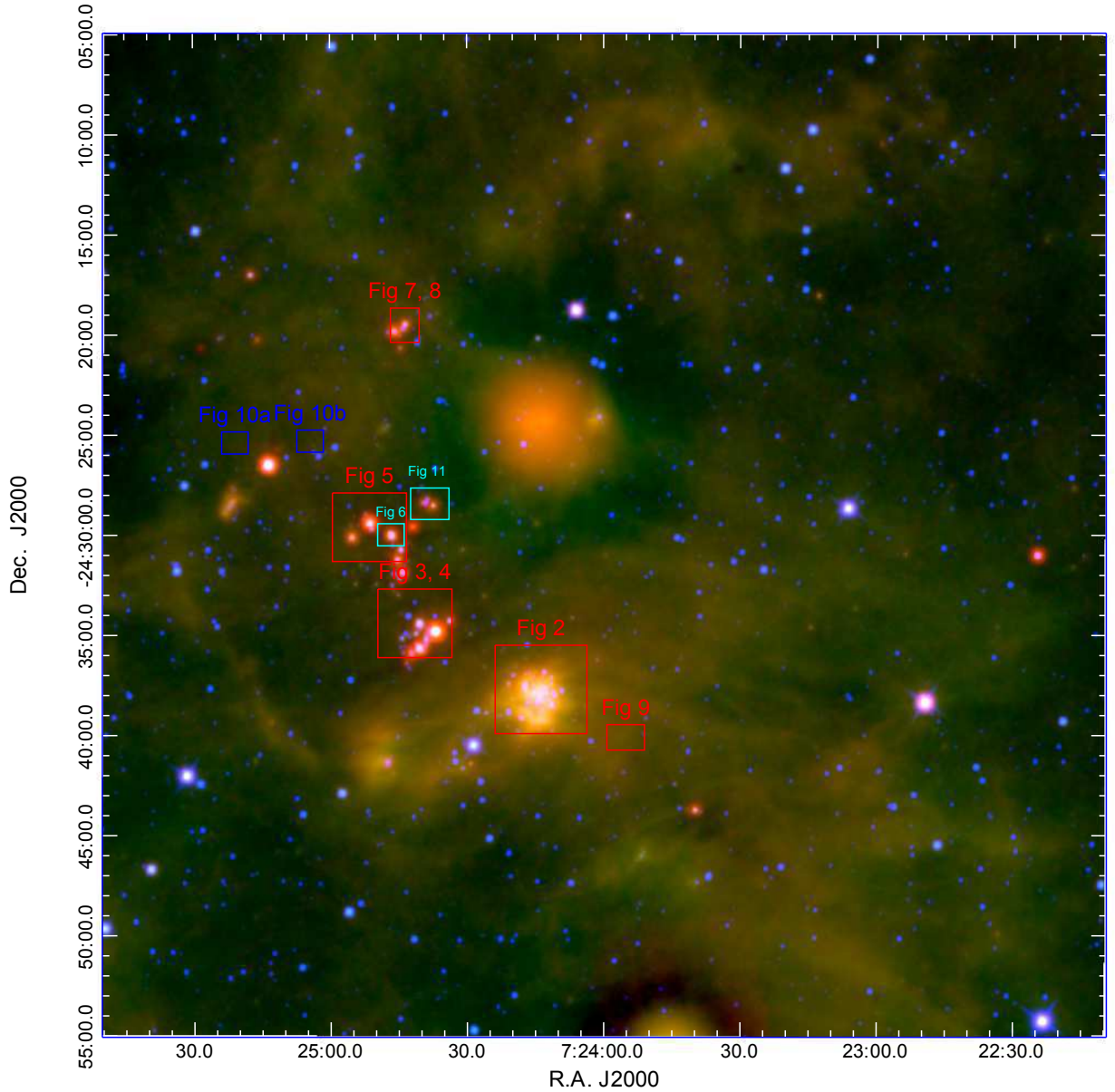


Figure 12. A WISE Band 2 ($4.6 \mu\text{m}$; blue), Band 3 ($12 \mu\text{m}$; green), and Band 4 ($22 \mu\text{m}$; red) image showing the field around Lynds 1664. As in Figure 1, the boxes mark indicate the locations of the various figures.

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